NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3575

BURNING VELOCITIES OF VARIOUS PREMIXED TURBULENT PROPANE FLAMES ON OPEN BURNERS

By Paul Wagner

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Washington
October 1955

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3575

BURNING VELOCITIES OF VARIOUS PREMIXED TURBULENT PROPANE FLAMES ON OPEN BURNERS

By Paul Wagner

SUMMARY

Turbulent burning velocities for premixed propane flames were measured at room temperature and at atmospheric pressure. The turbulent-burning-velocity measurements were made for systems of various laminar burning velocities, densities, and viscosities. These properties were varied by (1) replacing the nitrogen of the air with argon or helium, and (2) varying the oxygen concentrations in the propane-oxygen-nitrogen mixtures. Each set of turbulent-burning-velocity data was taken in a variety of burner sizes and over a velocity range.

The experimental data were correlated by a function of the form

$$\frac{U_T}{U_L} \propto Re^a$$

where U_T and U_L are turbulent and laminar burning velocities, respectively, Re is Reynolds number, and the exponent a was different for systems having various diluents (i.e., nitrogen, argon, and helium).

Measurements were made of the axial fluctuating-velocity component of the turbulent stream issuing from the burner port. The intensity of turbulence appeared to be dependent upon the nature of the diluent. Consideration of the data in terms of the measured turbulence parameters was a small over-all improvement. However, this change was in the direction of better correlation.

SYMBOLS

The following symbols are used in this report:

D	burner inside diameter, cm
h	mean flame height, cm

k	constant
L	burner length, cm
l	turbulence scale, cm
Re	Reynolds number based on pipe diameter, DU/ν
Re'	"turbulence" Reynolds number, Du'/ν
r	radius at base of mean flame surface, cm
S	area, sq cm
S_{av}	mean flame-surface area, sq cm
S_L	laminar flame-surface area, sq cm
T	equilibrium flame temperature, ^{O}K
U	mean stream velocity in axial direction, cm/sec
U_L	laminar burning velocity, cm/sec
U_T	turbulent burning velocity, cm/sec
u	local mean velocity in axial direction, cm/sec
$u' = \sqrt{\overline{u^2}}$	root mean square value of fluctuating velocity component in axial direction, cm/sec
v	volumetric flow rate, cc/sec
X	mole fraction
α	mole fraction of oxygen, O_2/O_2 + inert
ϵ	eddy diffusivity, sq cm/sec
$\nu = \frac{\mu}{\rho}$	kinematic viscosity, sq cm/sec
Φ	equivalence ratio
ρ	density, g/cc
μ	absolute viscosity, g/(sec)(cm)

3786

Subscripts:

i	i^{th} species
mix	"of the mixture"
j	a particular mixture

Superscript:

a	empirically determined exponent

INTRODUCTION

The requirements of jet-aircraft engines have indicated an ever increasing need for understanding the mechanism governing the high volumetric heat-release rates of a fuel-air mixture. Research in turbulent combustion has been directed to this general end. The specific object of the work presented in this report was to investigate the burning velocities of premixed open propane turbulent flames and to study the effect of turbulence and turbulent-flow parameters on a variety of these flames.

A flame stabilized in a laminar stream at the port of an open burner exhibits a clearly defined combustion zone; the volumetric flow of the unburned mixture divided by the surface area of the combustion zone is defined as the laminar burning velocity. The maximum value of the laminar burning velocity is a physical property of the system and as such characterizes the system. Application of a similar characterization to turbulent flames is desirable. However, a flame situated in a turbulent stream apparently has a rapidly fluctuating combustion zone, which shows no sharp separation from either the burned or the unburned gas, and the flame-surface area has not yet been directly measured. Therefore, the criterion applied to the laminar case cannot be applied to the turbulent case. The analog of the laminar burning velocity, as applied to the turbulent case, was given by Bollinger and Williams in reference 1 wherein the flame surface area is replaced by the area of a surface that defines the position of maximum luminous intensity of the flame brush. Considerable effort has been made to describe the relation between such a turbulent burning velocity and the aerodynamics of the flow system (refs. 2 to 5). Theories developed from this physical picture must be evaluated in terms of variables that are difficult to measure and cannot be reliably calculated at this time. It is for this reason that the present work is primarily an empirical treatment.

Measurements were made to determine the effect of laminar burning velocity, burner diameter, mean stream velocity, and kinematic viscosity of the unburned gas on the turbulent burning velocity. Laminar burning velocities were varied by (1) increasing the oxygen concentration of the propane-air flames, and (2) replacing the nitrogen of the air by argon or helium. Viscosities and densities were also changed by replacement of the inert component.

Hot-wire-anemometer measurements indicate that the longitudinal component of the fluctuating velocity changes upon substitution of argon or helium for the nitrogen, so that a further consequence of the substitution is to alter the turbulent intensity of the cold flow. Laminar burning velocities were varied from 35.5 to 124 centimeters per second. Measurements up to a maximum Reynolds number of 26,000 were made in five burners with diameters ranging from 0.639 to 1.890 centimeters. 3786

BASIC CONSIDERATIONS

Turbulent Burning Velocity

The laminar burning velocity of a flame seated at the port of an open burner is given by

$$U_L = \frac{V}{S_L} \tag{1}$$

The analogous quantity for turbulent flames has been defined in reference 1 as

$$U_T = \frac{V}{S_{av}} \tag{2}$$

This definition is required since no direct measurement of the surface area of a turbulent combustion wave is known at this time. The physical significance of such a definition is rooted in the concept of an extended, oscillating flame surface. In a direct photograph of a turbulent flame, where the time of exposure is long compared with the average time of fluctuation, the inner and outer envelopes of the flame brush are rather clearly defined (see fig. 1). The photographic density on such a photograph is a maximum at the position where the flame spends the longest time. In practice, this maximum appears about halfway between the inner and outer boundary of the brush. The position of the maximum is schematically shown in figure 2. The area of the surface through this position of maximum intensity is the S_{av} in equation (2). This surface will be referred to as the "mean flame surface."

Wohl and Shore (ref. 6) have probed turbulent butane-air flames in order to determine the region where the oxygen is being consumed at the maximum rate. They find that this region coincides with the region of maximum luminosity. These experiments suggest that the mean flame surface of a turbulent flame is the significant property to be used in turbulent burning-velocity determination.

Flow Considerations

To effect a variation in Reynolds number for pipe induced turbulence, the characteristic dimension of the pipe, linear velocity, and kinematic viscosity of the fluid must be changed. These changes were made by utilizing burners of different diameter, controlling the total flow rate, and replacing the nitrogen of the air with either argon or helium. These variables could be controlled either singly or in combinations.

The minimum requirements for assurance of fully developed turbulence in a pipe are not predictable (ref. 7). It is known, however, that inlet conditions of the fluid, roughness of the inside of the pipe wall, and the length-to-diameter ratio L/D of the pipe are important. It is to be expected, then, that published attempts to specify minimum L/D for fully developed turbulence are inconsistent. This is found to be the case. Previous work (refs. 7 to 9) indicates that the minimum allowable L/D is about 50. For the present work, all pipes were chosen so that the L/D was greater than 50 and the onset of turbulence was indicated at a Reynolds number of 2100 for the cold flow.

Laminar Burning Velocities

Substitution of either argon or helium for the nitrogen in the propane-air system will be manifested as a change in the laminar burning velocity (ref. 10). Also, the difference in heat capacity between nitrogen and the inert gases results in a flame temperature which is about 300° C higher for these gases. Laminar burning velocity may also be increased by increasing the oxygen content of the unburned mixture. The oxygen content was increased to change the burning velocity without appreciably affecting the viscosity or density of the approach stream flow.

EXPERIMENTAL DETAILS

General Description of Apparatus

The apparatus used in this investigation was a bench-scale flow system of conventional design similar to that described in reference 11. Air, propane, oxygen, helium, and argon were individually metered by means of calibrated critical-flow orifices to give desired mixture compositions and flow rates. The piping distance from the orifices to the burner was sufficient to ensure thorough mixing. Dynamic variables were controlled by appropriate choice of total flow rate, burner size, and mixture composition.

After mixing, the gases were passed through the burner and ignited at the port. In order to stabilize the turbulent flames, some of the combustible mixture was diverted to an annular pilot. The pilot flame was adjusted for the minimum flow necessary to prevent flame blow-off. To exclude anomalous temperature effects due to the heating of the burner lip by the flame, the upper part of the burner and the burner lip were water cooled. The details of the burner construction are shown in figure 3.

The temperatures of the inflammable mixtures and of the coolant were 3786
measured by thermocouples embedded in the apparatus at appropriate positions. The measured temperatures were constant for all the experiments. All measurements were made at normal room temperature and at atmospheric pressure.

Burners

In order to best assure fully developed pipe turbulence, burners with a L/D greater than 50 were used. The fact that no flames were laminar at $Re = 2100$ was taken as an indication that the L/D chosen was satisfactory. The dimensions of the burners used are given in the following list:

Burner inside diameter, cm	Length-diameter ratio, L/D
0.639	140
1.016	135
1.119	110
1.459	95
1.890	73

Materials

Gases. - Except for the use of service air, all gases were bottled and the manufacturer's stated purity was 99 percent or better. The gases were piped directly from either the tanks or from the building service-air supply to the critical-flow orifices and used without further treatment.

Composition of inflammable mixtures. - The chemical compositions of the combustible mixtures were kept constant across any one set of experiments. That is, for mixtures of propane, oxygen, nitrogen; propane, oxygen, helium; and propane, oxygen, argon, the fuel concentration was kept constant at 105 percent of stoichiometric, and the oxygen-to-total-noncombustible fraction was maintained at the normal atmospheric value of $\alpha = 0.209$. The oxygen-enriched mixtures were measured at 100 percent of the fuel-oxidant equivalence value, and the oxygen-to-total-noncombustible fractions were $\alpha = 0.27$ and $\alpha = 0.33$.

DETERMINATION OF U_T/U_L

Measurement of Turbulent Burning Velocity

3786

Measurement of mean flame-surface area. - Bollinger and Williams (ref. 1) used a mean flame surface based on a visual estimate of the position of maximum intensity. More recent workers (refs. 4 and 12) have used the densitometer or ion-gap-probe method to locate the region from which the mean flame-surface area may be measured. Both Clark and Bittker (ref. 12) and this author have compared the results of mean flame-area measurement as determined by both the densitometer and visual estimate method. The results are the same within the limits of experiment. The absolute magnitude of the differences average less than 5 percent. Bollinger and Williams (ref. 1) determined the mean area of their flames on the assumption that the shape of the flame was closely approximated by a right circular cone. However, the shape of many turbulent flames, especially of short flames, does not approximate that of a cone. Consequently, a method of area calculation was sought that would be more generally applicable than the Bollinger and Williams method.

Photographs of turbulent flames (figs. 1(a) and (b)) showed that the average flame-surface area could be described analytically for the majority of the experiments as a paraboloid of revolution. The area for such a surface is given by

$$S = \frac{2\pi}{3}\left(\frac{r^2}{2h}\right)^{1/2}\left[\left(2h + \frac{r^2}{2h}\right)^{3/2} - \left(\frac{r^2}{2h}\right)^{3/2}\right] \tag{3}$$

Equation (3) may be simplified; for the case where $r^2/2h$ is small compared with $2h$, this equation reduces to

$$S = \frac{4\pi}{3} rh \tag{3a}$$

In practice, it is found that the approximate equation is good for all flames where $h \geq 2r$; and in the limiting case where $h = 2r$, the difference in areas calculated by equations (3) and (3a) is about 2 percent. For flames where h is smaller than $2r$, equation (3) must be used. The average difference between areas calculated by equation (3a) and areas measured by numerical integration over the surfaces determined by the densitometer and by visual estimation was about +4 percent. Since the reproducibility for either type measurement is not better than ±3 percent, the agreement is satisfactory. It must be noted that this method breaks down when very short or irregularly shaped flames are considered. For these cases, one must revert to the most direct method possible. For flames which could not be handled analytically, such as the oxygen-enriched propane-air flames, the numerical integration method was used.

Calculation of turbulent burning velocity. - Direct photographs were made of turbulent flames. Mean flame-surface areas were measured from the negatives, as has been described in the section BASIC CONSIDERATIONS. From the known values of the inlet conditions to the pipe, the volumetric flow rates were calculated. The turbulent burning velocity was then determined by the relation (eq. (2))

$$U_T = \frac{V}{S_{av}}$$

Analysis of combustion products. - In order to use the turbulent burning velocity in the computation of a quantity such as heat-release rate, the degree of completion of the combustion reaction must be known. It is for this reason that the degree of completion of the combustion reaction has been a matter of some interest (ref. 13). To clarify this point with respect to the experiments carried out in the present work, stoichiometric propane-air flames with Re = 10,000 were sampled at the apex of the outer envelope of the turbulent flame brush. The combustion products were then analyzed by means of a gravimetric combustion-train-type apparatus. The analysis was compared with the calculated equilibrium values of the reaction products, assuming equilibrium flame temperature. The following table is a comparison of a set of typical results with the calculated values.

Reaction product	Analyzed, percent	Calculated, percent
N_2	72.3	72.3
CO_2	10.0	10.0
CO	1.0	1.3
O_2	1.1	.6
H_2O	15.1	15.1
H_2	.3	.3
C_3H_8	.01	.0

From this table it may be seen that, in the cases considered, the combustion reaction apparently goes to completion. However, as is pointed out in reference 13, it should not be concluded that this is always the case.

3786

3786

CM-2

Measurement of Laminar Burning Velocity

For the best self-consistency in the data, laminar burning velocities for the propane-oxygen-nitrogen, propane-oxygen-helium, and propane-oxygen-argon systems were measured in the apparatus.

Laminar burning velocities were determined by the total-area method from direct photographs. The measured values were then plotted as a function of equivalence ratio (fig. 4), and the maximum value of the burning velocity was then read from the curve. The maximum value of the burning velocity is the quantity which is referred to in this report as the "normal" or "laminar" burning velocity.

For the oxygen enriched mixtures, the work of reference 11 on the effect of oxygen concentration on propane-air burning velocities was utilized. On the basis of these results, sufficient oxygen was added to the propane-air mixture to increase the burning velocity by factors of two and three, respectively. The burning velocities and flame temperatures are shown in the following table:

Composition	Mole fraction of oxygen, α	Laminar burning velocity, $U_{L(max)}$, cm/sec	Calculated equilibrium flame temperature, T, $^{\circ}K$
Propane, nitrogen, oxygen	0.21	35.5	2281
Propane, nitrogen, oxygen	.27	71.0	2520[a]
Propane, nitrogen, oxygen	.33	106.5	2635[a]
Propane, oxygen, helium	.21	124	2574
Propane, oxygen, argon	.21	72.5	2574

[a]Ref. 11 by interpolation.

DETERMINATION OF REYNOLDS NUMBER

Pipe Reynolds Number

In order to use Reynolds number as a meaningful parameter, the condition of dynamic similarity must be fulfilled. This is accomplished for systems with fully developed pipe turbulence.

Fully developed pipe turbulence is not predictable from the geometry and flow velocities of a system (ref. 7). Indirect evidence that the flow pattern was fully developed in the present experiments is (1) the construction of the apparatus resulted in turbulent entry conditions, (2) the length-diameter ratio of all pipes was greater than 50, and (3) measured turbulent intensities were independent of stream velocity. In practice, the Reynolds number was changed by varying the velocity, the pipe diameter, and the kinematic viscosity.

Calculation of kinematic viscosity. - Kinematic viscosities used to calculate Reynolds numbers for the gas mixtures were obtained from the relation

$$\nu_{mix} = \sum_i \nu_i X_i \tag{4}$$

For gaseous mixtures, application of such a relation is generally an inexact approximation (ref. 14). However, calculated values from equation (4) when compared with values calculated by more exact methods (ref. 14) indicated that the maximum error would be of the order of 5 percent.

Turbulence Reynolds Number

The Reynolds number may be computed in a variety of ways, depending on what are chosen as characteristic dimensions and velocities. Inasmuch as the turbulence in the stream is pertinent to this investigation, it is desirable to consider the experimental data in terms of the parameters which characterize the turbulence. These parameters are the intensity and the scale of the turbulence. The scale may be taken as being directly proportional to the pipe diameter (refs. 8 and 9). The component of intensity along the axis of the tube was measured by means of a constant-temperature, hot-wire anemometer. The percentage intensity, as measured, differed with the composition of the gas stream for similar flow conditions. The intensity is defined as

$$\sqrt{\frac{\overline{u^2}}{u}} \tag{5}$$

Calculation of the relation between the local mean velocity in the axial direction and the mean stream velocity (ref. 15) shows that

$$\frac{u}{U} \cong \text{Constant} \tag{6}$$

for all the compositions considered. This means that an appropriate velocity to use in calculating a Reynolds number based on the nature of the turbulence is $u' = (\overline{u^2})^{1/2}$, which may be determined from

$$u_j' = k_j U \tag{7}$$

where k takes on different values, depending on the mixture composition. When the pipe diameter is taken as a measure of the scale l the Reynolds number of turbulence becomes

$$Re'_j = \frac{u'_j l}{\nu_j} = \frac{k_j UD}{\nu_j} \tag{8}$$

The similarity of this parameter to that suggested by Damköhler (ref. 2) will be discussed later.

Turbulence intensity measurements. - To determine the effect of the composition change on the nature of the turbulent stream issuing from the burner port, the intensity of the axial component of the fluctuating velocity was measured. The intensity is defined as the ratio of the root mean square value of the fluctuating velocity component divided by the local mean stream velocity at the point of measurement. The use of the constant-temperature, hot-wire anemometer for this type of measurement has already been described (ref. 16). All measurements were made at the axis of the tube with the hot wire at zero distance from the port. No corrections were made for wire length. Inasmuch as intensity measurements of this type have been made for air as a function of flow velocity and distance from the burner mouth (ref. 15), the information sought for this work consisted of the relative values of the axial fluctuating velocity component for mixtures containing nitrogen, argon, or helium with comparable amounts of oxygen. The oxygen concentration was the same as that in the atmosphere. Measurements were made for comparable flow conditions, that is, similar velocities and similar Reynolds numbers. The apparent constancy of the percentage intensity with flow rate was taken as an indication that fully developed pipe turbulence had been attained. The measured values of the intensity were as follows:

Composition	Intensity
Nitrogen, oxygen	0.041
Helium, oxygen	.020
Argon, oxygen	.049

RESULTS

Experimental Results

Turbulent burning velocities were measured over the range permitted by the particular mixture and capacity of the apparatus in as wide a variety of burners as possible. The Reynolds number for cold flow was varied from the onset of pipe turbulence (about 2100) to maximum values of 6000 for propane, oxygen, helium; 26,000 for propane, oxygen, argon; and 20,000 for propane, oxygen, nitrogen. The data are reproduced in table I.

Behavior of the burning-velocity ratio as a function of pipe Reynolds number is shown in figure 5. The general trends for each of the systems is the same in that an increase in Reynolds number is attended by an increase in burning-velocity ratio. However, the dependence on Reynolds number of the burning-velocity ratio differs, depending on the composition of the mixture. This is shown in figures 5 and 6. Figure 5(a) shows the data for the propane-oxygen-nitrogen system and the line of least squares which best fits the data. Figures 5(b) and (c) are similar plots for the propane-oxygen-argon and propane-oxygen-helium systems, respectively. The dashed lines on figure 5 are the predictions made from the Bollinger and Williams (ref. 1) correlation compared with the measured turbulent burning velocities. Figure 6 is a comparison of the least-squares treatment showing the difference in Reynolds number dependence for the systems with various diluents. 3786

Figure 7 shows the dependence of the ratio of turbulent to laminar burning velocity U_T/U_L on the Reynolds number that is calculated from the results of the turbulence intensity measurements. The symbol Re' is referred to as the "turbulence Reynolds number" in order to distinguish this parameter from the Reynolds number calculated from the mean stream velocity.

Comparison with Previous Work

Bollinger and Williams (ref. 1) presented a correlation of the form

$$\frac{U_T}{U_L} = 0.18\ Re^{0.24}\ d^{0.26} \tag{9}$$

based on measurements made with acetylene-, ethylene-, and propane-air flames. It is of interest to test the generality of such a correlation, since the Reynolds number variation involved only small changes in density and viscosity, whereas in the present work, all four of the variables from which the Reynolds number is computed have been varied.

The experimental data are compared with the predictions made from the correlation of Bollinger and Williams (ref. 1) in figure 5. The dashed lines of figure 5 represent the analytical plot of equation (9); there is a separate line for each burner size. The dependence of the burning velocity on the Reynolds number is predicted very well, in general. However, the predicted burning-velocity-ratio dependence on the burner diameter is not observed for any of the systems.

DISCUSSION OF RESULTS

It is felt that for the best practical application, the data should be treated in the simplest possible manner. Inasmuch as present day theories appear to be based on an inadequate model of turbulent combustion, an evaluation of the data in terms of theory would be unreliable at this time. For these reasons the empirical approach was used. The data indicated a correlation between burning-velocity ratio and Reynolds number.

From figure 5, the turbulent burning-velocity dependences on pipe Reynolds number are

For propane, oxygen, nitrogen:

$$\frac{U_T}{U_L} \propto Re^{0.25} \tag{10a}$$

For propane, oxygen, argon:

$$\frac{U_T}{U_L} \propto Re^{0.44} \tag{10b}$$

For propane, oxygen, helium:

$$\frac{U_T}{U_L} \propto Re^{0.20} \tag{10c}$$

A Reynolds number may also be computed from the measurements on intensity. Such a parameter has been defined in equation (8) as

$$Re_j' = \frac{u_j' l}{\nu_j} = k_j \text{ Re (pipe)}$$

This parameter is the same as that used by Damköhler (ref. 2) in the development of his theory of turbulent combustion, except that he denoted the product $u'l$ by ϵ. This definition is subject to some discussion. First the reason for even considering the nature of the turbulence is that the turbulence is thought to have a definite effect on the propagation rates of the flames. However, the nature of the turbulence within the flame itself is to all intents and purposes unknown experimentally. Therefore, any treatment involving turbulence parameters must be an approximation, and the quality of such approximations will be indeterminate until more is known about the interaction between a turbulent field and a combustion wave. The second qualification is that while there is considerable known about the turbulent field within a circular pipe, the field at the exit of a pipe is in the process of change and the values of the scale and intensity are changing in a manner which has not yet been generally described. Since the combustion experiments have been conducted at the exit of the pipe, where conditions are different from point to point, the one approximation to be made is to compare values of the scale and the intensity at a given point. The values of u' used to calculate Re' were measured at zero distance from the exit; burner diameters were used as the measure of the scale since the scale should not be affected by the composition.

3786

Figure 7 shows the least-squares lines of figure 6 plotted as U_T/U_L against Re'. The value of Re' was calculated from the following equations:

For propane, oxygen, nitrogen:

$$Re' = \frac{0.041\ UD}{\nu} \tag{11a}$$

For propane, oxygen, argon:

$$Re' = \frac{0.049\ UD}{\nu} \tag{11b}$$

For propane, oxygen, helium:

$$Re' = \frac{0.020\ UD}{\nu} \tag{11c}$$

The spread of the correlation plots is somewhat less than when the cold-flow Reynolds number is used although the slopes are unaffected. Also, while these considerations do not correlate all the data, the trend is toward better agreement and this, in turn, argues for the desirability of using measurements on the turbulent field in the treatment of turbulent burning-velocity work.

Statistical considerations. - In order to complement the treatment of the results, it was felt that statistical measures of the significance of the data should be computed.

3786

The first point of importance is determination of whether the grouping of the data according to the inert diluent (nitrogen, helium, or argon) is correct. That is, should the data have been grouped into more than or less than three classes? This decision can be made by examining the slopes of the lines of the logarithmic plot in terms of the statistical "t" test of significance (ref. 17). Given two groups of data to which the method of least squares has been applied, the "t" tests will yield the probability that a difference in slope best expresses the trend of the data. The test shows that, for the data presented in this report, (1) the probability is 99 percent that the least-square line for the nitrogen data should have a different slope from that for the argon data; (2) the probability is 99 percent that the argon data should have a different slope from that for the helium data; and (3) the probability is 90 percent that the helium data should have a different slope from that for the nitrogen data. Thus, it appears quite probable that at least three groupings of the data are realistic. Should more than three groupings have been used? Careful examination showed that the nitrogen data had the largest spread, and, therefore, these data were broken up into two groups, that in which $\alpha = 0.209$ and that in which $\alpha > 0.209$. Analysis showed that the probability that these data should be expressed as two lines of different slope was 40 percent. This case is not as clearly defined as the previous cases, however, since the weighting is 60 to 40 percent for considering all these data together, this was done.

The second point of importance is to determine how much better than Re is Re' with respect to an over-all correlation. The proper measure of significance here is the standard error of estimate. This describes how closely the data points would cluster about a single line. The result of the examination showed that the standard error of estimate on the Re' basis was one-half of the value obtained on the Re basis. In other words, when all the data are considered, Re' is twice as good as Re for a correlation with burning-velocity ratio.

Remarks on theory. - Theories of turbulent burning velocity generally predict that the burning-velocity ratio will increase with an increase in intensity. This trend is borne out in this report, but only for systems of a given diluent. The measurements of the turbulence allow some speculation about the generality of these theoretical observations inasmuch as it is possible, from the data, to compare burning velocities of different mixture compositions at similar values of the scale and intensity. When this comparison is made, different values of the turbulent burning-velocity ratio are found. For these cases, there seems to be no apparent relation between turbulent burning-velocity ratio and the intensity of the turbulence as measured in this work.

SUMMARY OF RESULTS

The investigation of turbulent burning velocity for premixed propane flames may be summarized as follows:

1. For a system of a given diluent at atmospheric pressure and room temperature, the turbulent-to-laminar-burning-velocity ratio is correlated by the Reynolds number.

2. The dependence of the burning-velocity ratio on pipe Reynolds number is different for systems of different diluents.

3. The data are correlated better by considering a Reynolds number based on the intensity of the turbulence at the exit of the burner. This suggests that it is desirable to correlate turbulent burning-velocity data with turbulent-field characterization parameters.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 31, 1955

3786

REFERENCES

1. Bollinger, Lowell M., and Williams, David T.: Effect of Reynolds Number in Turbulent-Flow Range on Flame Speeds of Bunsen Burner Flames. NACA Rep. 932, 1949. (Supersedes NACA TN 1707.)

2. Damköhler, Gerhard: The Effect of Turbulence on the Flame Velocity in Gas Mixtures. NACA TM 1112, 1947.

3. Shelkin, K. I.: On Combustion in a Turbulent Flow. NACA TM 1110, 1947.

4. Karlovitz, Béla: A Turbulent Flame Theory Derived from Experiments. AGARD Selected Combustion Problems, Butterworths Sci. Pub. (London), 1954, pp. 248-262; discussion, pp. 263-274.

5. Scurlock, Arch C., and Grover, John H.: Experimental Studies in Turbulent Flames. AGARD Selected Combustion Problems, Butterworths Sci. Pub. (London), 1954, pp. 215-247.

6. Wohl, Kurt, and Shore, Leon: Experiments with Butane-Air and Methane-Air Flames. Ind. and Eng. Chem., vol. 47, no. 4, Apr. 1955, pp. 828-834.

7. Goldstein, Sydney, ed.: Modern Developments in Fluid Dynamics. Clarendon Press (Oxford), 1938, pp. 347-361.

8. Prandtl, Ludwig: Essentials of Fluid Dynamics. Hafner Pub. Co. (New York), 1952, pp. 166-168.

9. Gaydon, A. G., and Wolfhard, H. G.: Flames - Their Structure, Radiation, and Temperature. Chapman & Hall (London), 1953, pp. 15-16.

10. Morgan, Gerry H., and Kane, Walter R.: Some Effects of Inert Diluents on Flame Speeds and Temperatures. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co. (Baltimore), 1953, pp. 313-320.

11. Dugger, Gordon L., and Graab, Dorothy D.: Flame Velocities of Propane- and Ethylene-Oxygen-Nitrogen Mixtures. NACA RM E52J24, 1953.

12. Clark, Thomas P., and Bittker, David A.: A Study of the Radiation from Laminar and Turbulent Open Propane-Air Flames as a Function of Flame Area, Equivalence Ratio, and Fuel Flow Rate. NACA RM E54F29, 1954.

13. Wohl, Kurt, Shore, L., von Rosenberg, H., and Weil, C. W.: The Burning Velocity of Turbulent Flames. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co. (Baltimore), 1953, pp. 620-635.

14. Hirschfelder, Joseph O., Curtiss, Charles F., and Bird, R. Byron: Molecular Theory of Gases and Liquids. John Wiley & Sons, Inc., 1954, pp. 566-573.

15. Little, Barney H., Jr., and Wilbur, Stafford W.: Turbulence-Intensity Measurements in a Jet of Air Issuing from a Long Tube. NACA TN 2361, 1951.

16. Laurence, James C., and Landes, L. Gene: Auxiliary Equipment and Techniques for Adapting the Constant-Temperature Hot-Wire Anemometer to Specific Problems in Air-Flow Measurements. NACA TN 2843, 1952.

17. Youden, W. J.: Statistical Methods for Chemists. John Wiley & Sons, Inc., 1951, pp. 40-49.

TABLE I. - BURNING VELOCITY DATA FOR VARIOUS MIXTURES OF GASES

(a) Propane, oxygen, nitrogen

Burner diameter, D, cm	Equivalence ratio, Φ	Oxygen mole fraction, α	Mean stream velocity, U, cm/sec	Reynolds number, Re	Laminar burning velocity, U_L, cm/sec	Burning velocity ratio, U_T/U_L
1.890	1.05	0.209	239	3,015	35.5	1.30
			315	3,985		1.46
			397	5,016		1.35
			478	6,043		1.62
			569	7,186		1.67
			661	8,337		1.69
			742	9,353		1.78
			824	10,383		1.80
			840	10,586		1.83
1.119			395	2,788		1.12
			434	3,061		1.18
			471	3,324		1.20
			518	3,654		1.27
			555	3,921		1.22
			603	4,258		1.31
			650	4,589		1.31
			706	4,980		1.38
			745	5,258		1.47
			792	5,591		1.54
			838	5,922		1.56
			886	6,257		1.58
			933	6,588		1.60
			983	6,910		1.61
			886	6,257		1.59
			793	5,596		1.54
			707	4,990		1.46
			604	4,266		1.37
			557	3,937		1.38

3786

TABLE I. - Continued. BURNING VELOCITY DATA FOR VARIOUS MIXTURES OF GASES

(a) Continued. Propane, oxygen, nitrogen

Burner diameter, D, cm	Equivalence ratio, Φ	Oxygen mole fraction, α	Mean stream velocity, U, cm/sec	Reynolds number, Re	Laminar burning velocity, U_L, cm/sec	Burning velocity ratio, U_T/U_L
1.016	1.05	0.209	797	5,415	35.5	1.24
			1078	7,316		1.18
			1379	9,365		1.33
			1670	11,342		1.57
			1986	13,479		1.72
			2165	14,703		1.86
			2458	16,682		1.86
			2751	18,733		2.00
			2894	19,720		2.14
.639			733	2,957		1.12
			809	3,264		1.16
			894	3,605		1.19
			979	3,944		1.19
			1038	4,182		1.27
			1094	4,411		1.24
			1157	4,664		1.33
			1247	5,027		1.38
			1307	5,273		1.38
			1389	5,603		1.44
			1477	5,955		1.51
			1563	6,301		1.63
			1648	6,644		1.53
			1737	7,003		1.49
			1822	7,341		1.58
			1911	7,699		1.61
			1996	8,042		1.68
1.890	1.00	0.270	965	9,792	71.0	1.71
			868	8,781		1.59
			610	7,808		1.55
			530	6,784		1.39
			450	5,760		1.58
1.459	1.00		630	6,224		1.45

TABLE I. - Continued. BURNING VELOCITY DATA FOR VARIOUS MIXTURES OF GASES

(a) Concluded. Propane, oxygen, nitrogen.

Burner diameter, D, cm	Equivalence ratio, Φ	Oxygen mole fraction, α	Mean stream velocity, U, cm/sec	Reynolds number, Re	Laminar burning velocity, U_L, cm/sec	Burning velocity ratio, U_T/U_L
1.459	1.0	0.270	755	7,459	71.0	1.54
			890	8,793		1.61
			1024	10,117		1.70
			1152	11,382		1.83
1.016			1301	8,950		1.42
			1560	10,733		1.54
			1837	12,639		1.61
			2114	14,544		1.69
			2378	16,361		1.70
			2653	18,252		1.83
1.459		.330	836	8,259	106.5	1.68
			984	9,722		1.77
			1135	11,212		1.84
			1178	11,638		1.85
1.016			1725	11,868		1.61
			2031	13,973		1.64
			2342	16,112		1.80
			2644	18,190		1.86
			2849	19,600		1.93

3786

TABLE I. - Continued. BURNING VELOCITY DATA FOR VARIOUS MIXTURES OF GASES

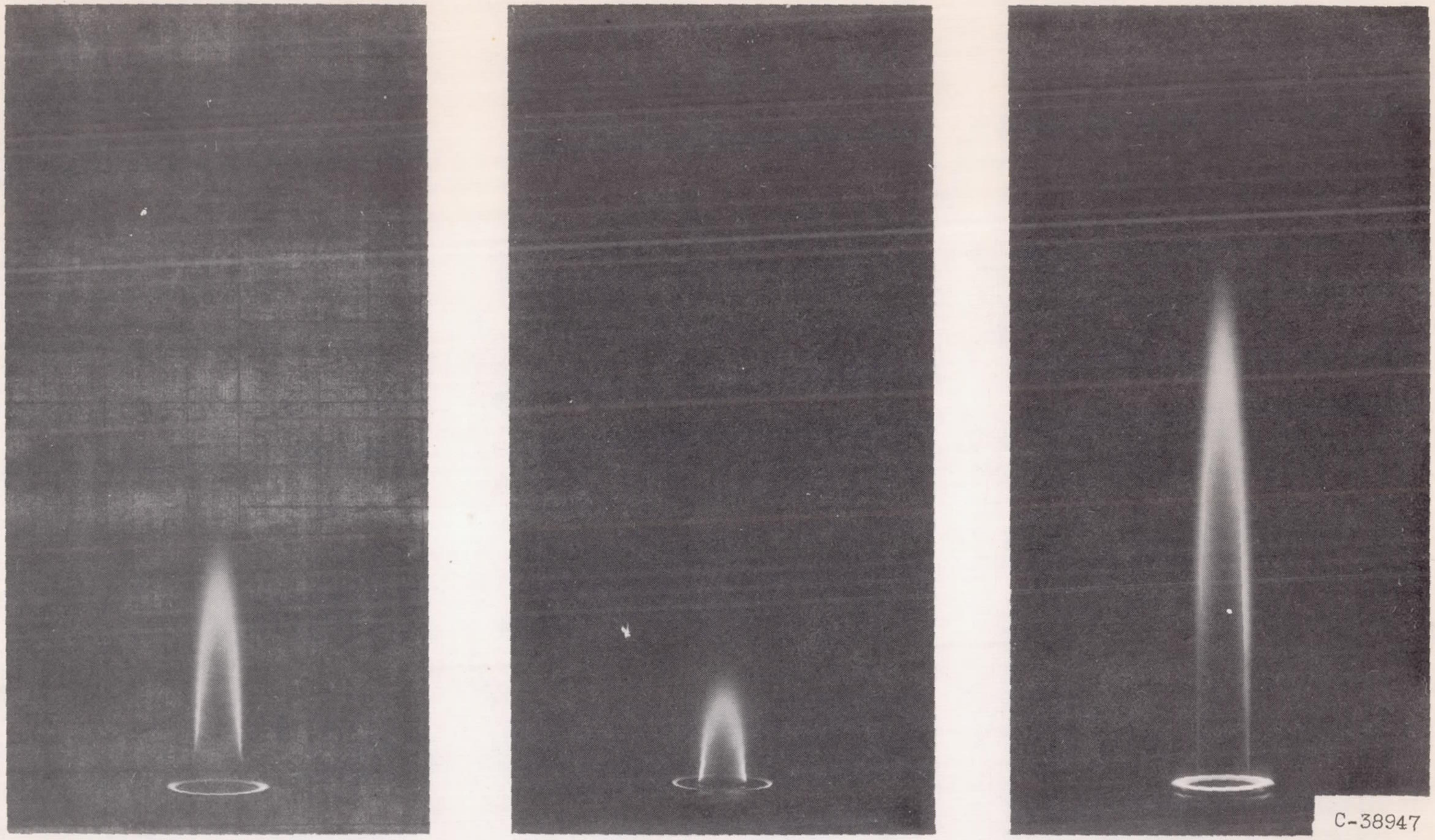
(b) Propane, oxygen, argon

Burner diameter, D, cm	Equivalence ratio, Φ	Oxygen mole fraction, α	Mean stream velocity, U, cm/sec	Reynolds number, Re	Laminar burning velocity, U_L, cm/sec	Burning velocity ratio, U_T/U_L
1.89	1.05	0.209	438	5,693	72.5	1.63
			544	7,075		1.69
			647	8,426		1.71
			755	9,833		1.85
			860	11,190		1.93
			966	12,577		2.03
			1041	13,552		2.12
1.119			377	2,987		1.09
			444	3,523		1.09
			508	4,030		1.06
			575	4,561		1.18
			631	5,012		1.22
			699	5,553		1.32
			755	5,992		1.32
			821	6,518		1.42
1.016			657	4,600		1.26
			989	6,923		1.22
			1527	10,670		1.73
			1896	13,249		2.06
			2256	15,764		2.22
			2635	18,438		2.35
			3005	21,012		2.24
			3378	23,637		2.42
			3701	25,897		2.48

TABLE I. - Concluded. BURNING VELOCITY DATA FOR VARIOUS MIXTURES OF GASES

(c) Propane, oxygen, helium

Burner diameter, D, cm	Equivalence ratio, Φ	Oxygen mole fraction, α	Mean stream velocity, U, cm/sec	Reynolds number, Re	Laminar burning velocity, U_L, cm/sec	Burning velocity ratio, U_T/U_L
1.016	1.05	0.209	2046	2090	124.0	1.08
			2359	2410		1.11
			2755	2800		1.05
			3132	3190		1.08
			3520	3590		1.11
			3894	3960		1.02
			4030	4110		1.13
			4223	4300		1.14
			4350	4440		1.13
			4550	4640		1.17
			4604	4700		1.21
			5000	5090		1.19
			5290	5390		1.20
			5600	5710		1.21
			5940	6050		1.22
			6070	6180		1.17
.639			2830	1839		.86
			3100	2017		.93
			3429	2236		1.00
			3691	2402		1.04
			4012	2614		1.05
			4318	2808		.99
			4643	3019		1.02
			4902	3189		1.02
			5186	3374		1.06
			5457	3553		1.05

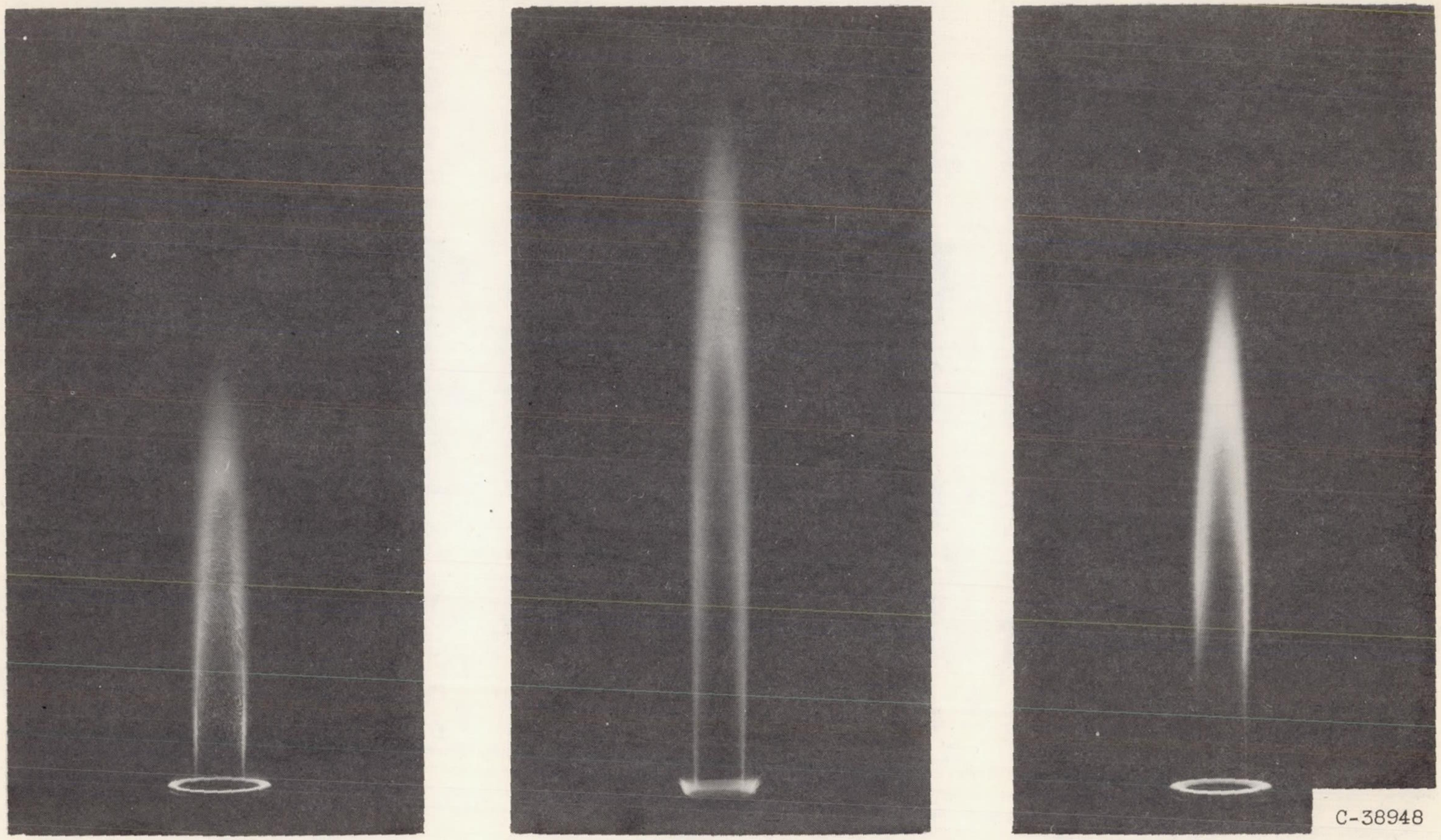


C-38947

Components	C_3H_8, air	C_3H_8, A, O_2	C_3H_8, He, O_2
Reynolds number	4150	3773	2595
Linear velocity, cm/sec	611	537	2525

(a) At similar Reynolds numbers.

Figure 1. - Relative appearance of turbulent flames. Burner diameter, 1.016 centimeters; mole fraction of oxygen, 0.21; equivalence ratio, 1.05.



Components	C_3H_8, A, O_2	C_3H_8, air	C_3H_8, He, O_2
Linear velocity, cm/sec	2329	2450	2307
Reynolds number	16,319	16,300	2368

(b) At similar velocities.

Figure 1. - Concluded. Relative appearance of turbulent flames. Burner diameter, 1.016 centimeters; mole fraction of oxygen, 0.21; equivalence ratio, 1.05.

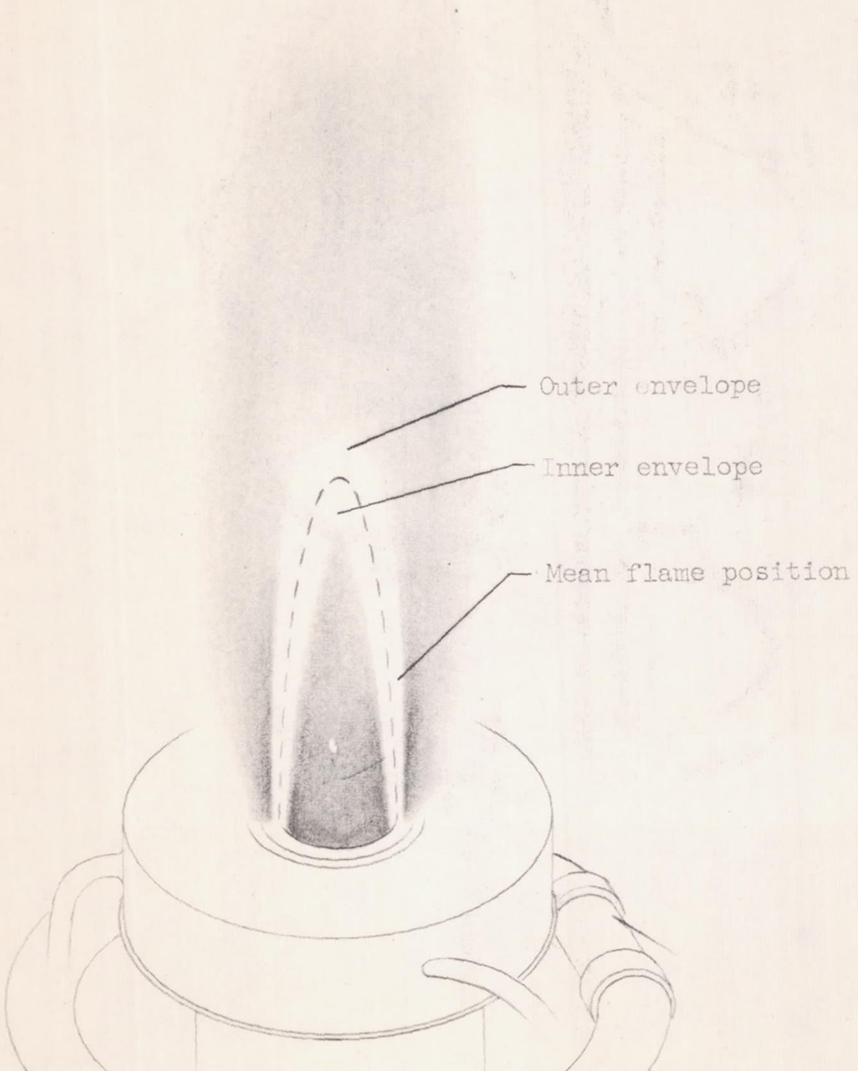


Figure 2. - Sketch representing time exposure of turbulent flame showing mean flame position.

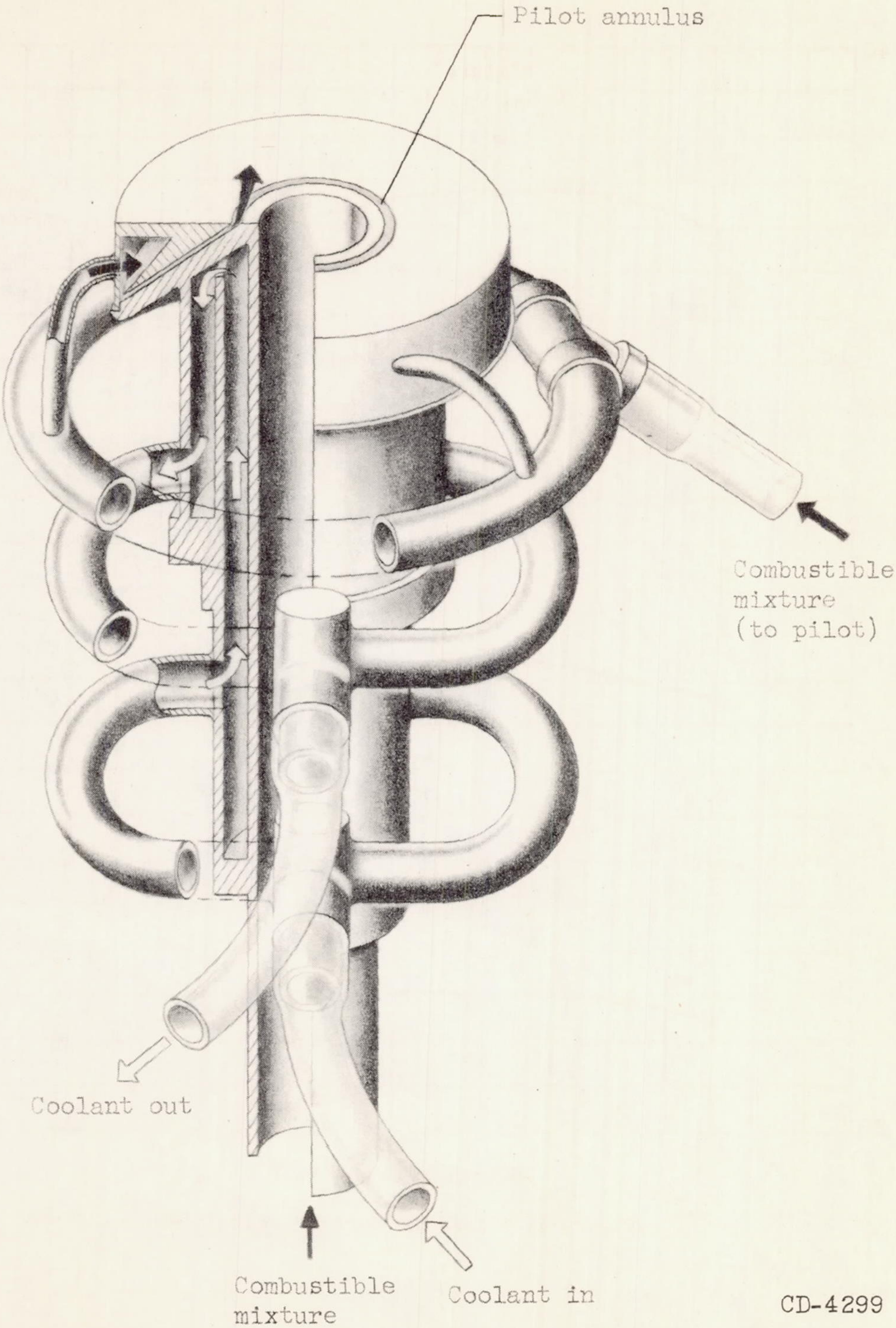


Figure 3. - Detail of burner showing piloting arrangement, cooling system, and burner exit.

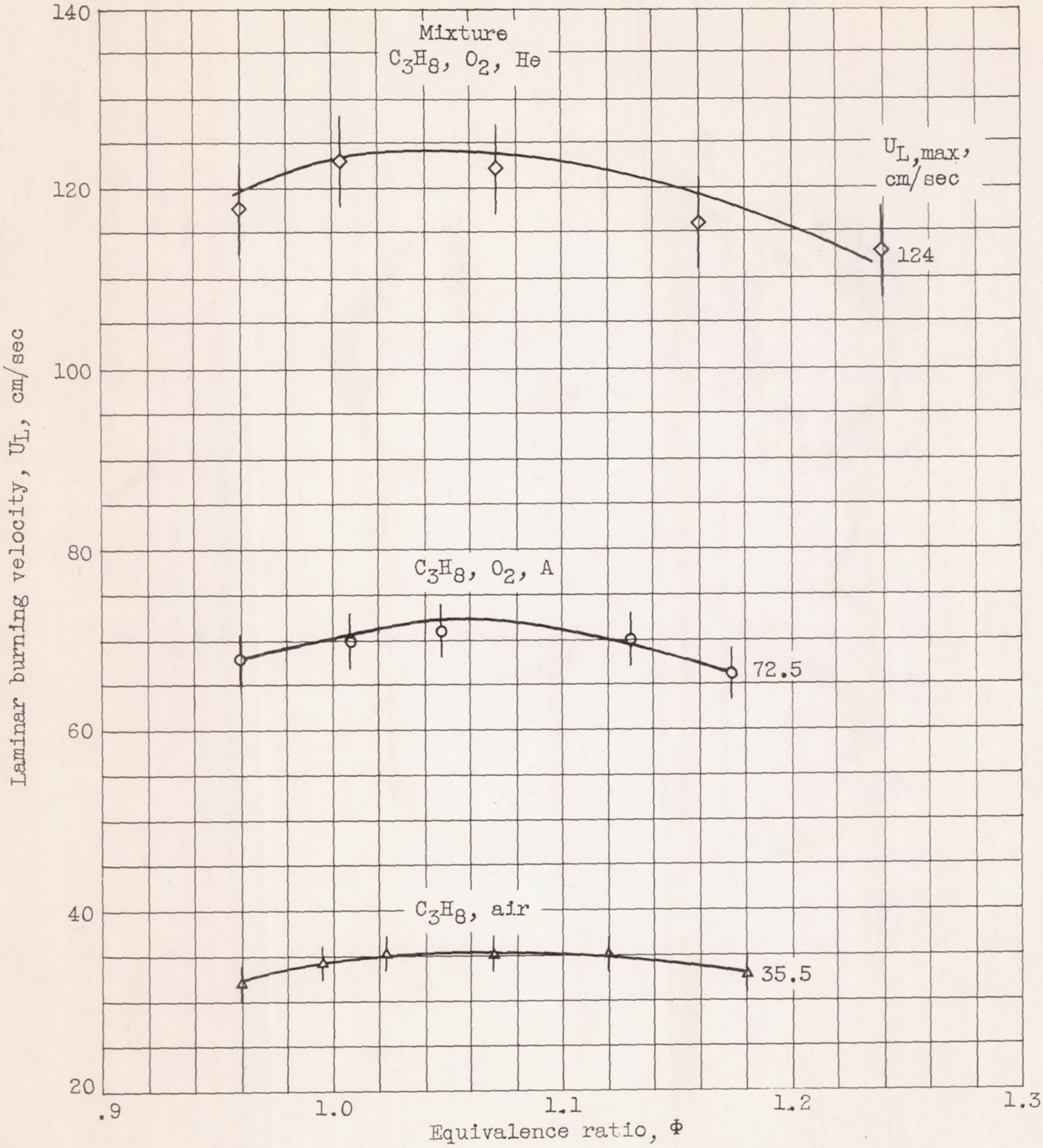
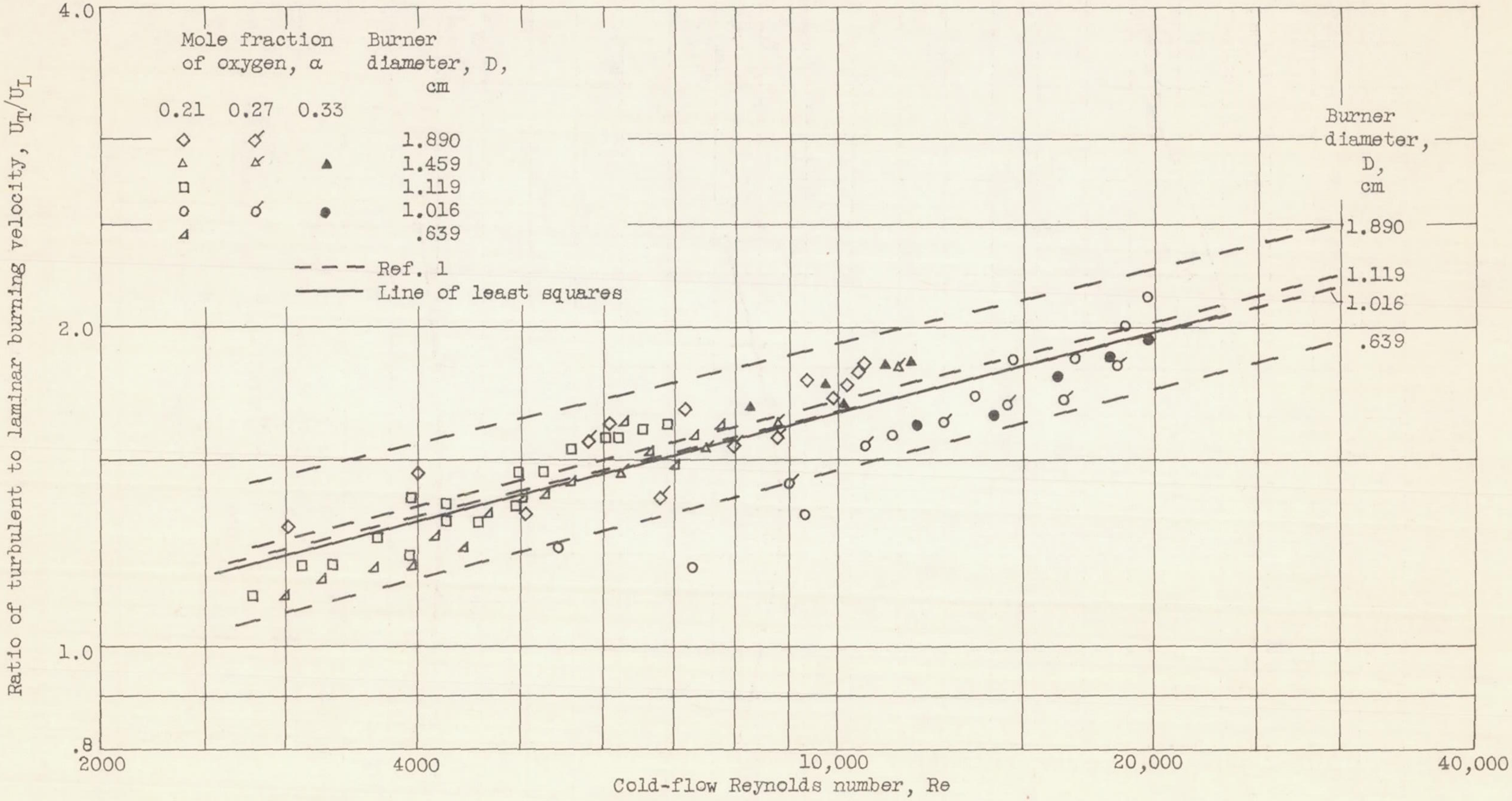
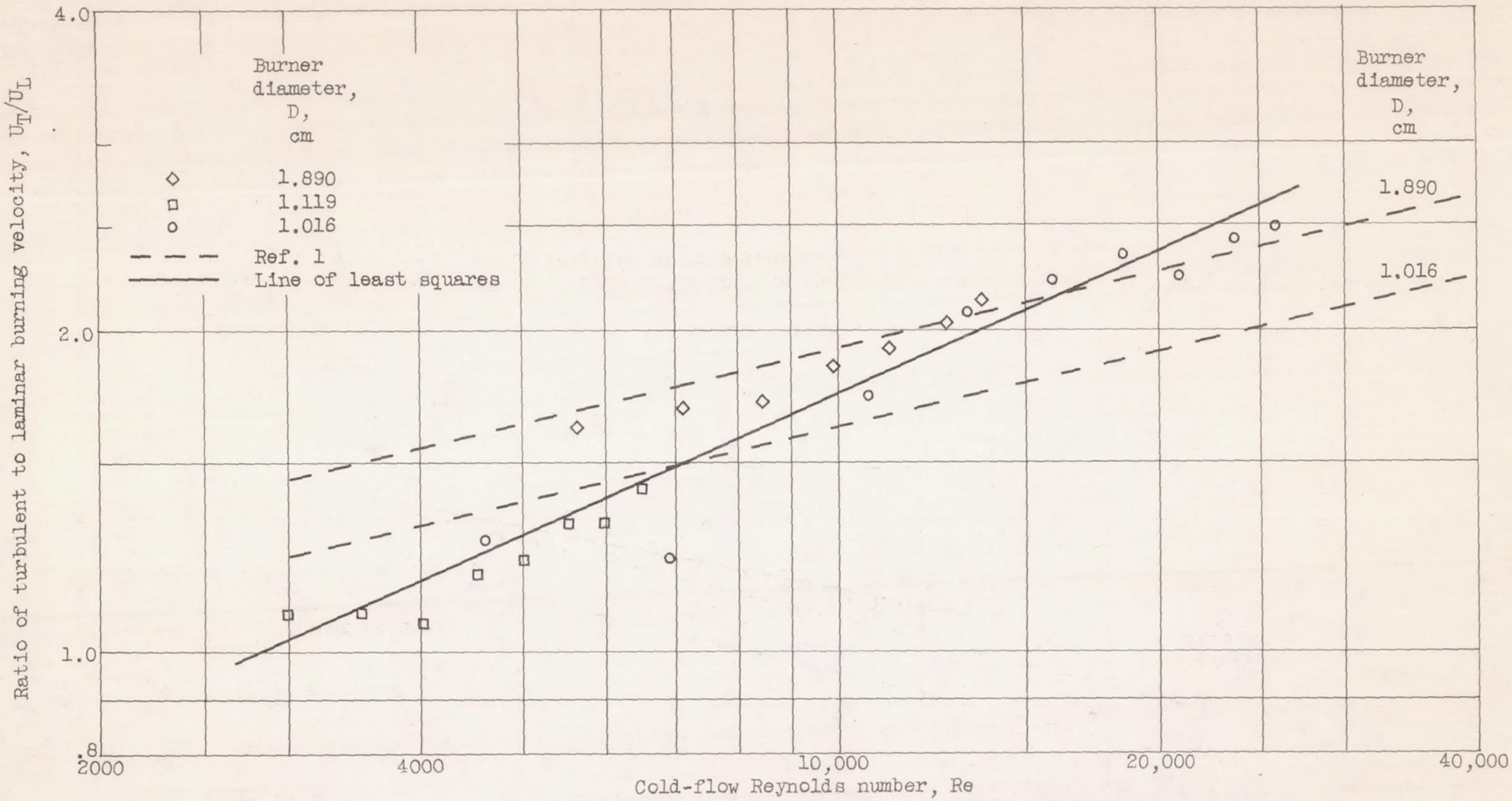


Figure 4. - Laminar burning velocities.



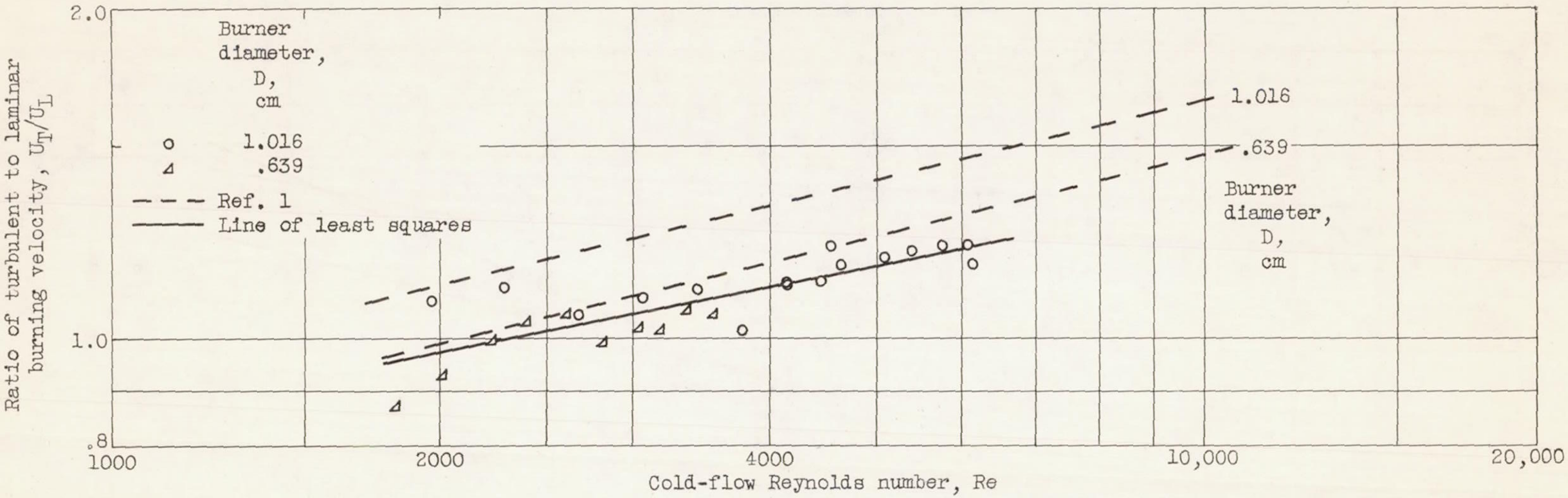
(a) Propane, oxygen, nitrogen.

Figure 5. - Effect of Reynolds number on turbulent burning velocity for various mixtures and comparison with predicted correlation of reference 1.



(b) Propane, oxygen, argon.

Figure 5. - Continued. Effect of Reynolds number on turbulent burning velocity for various mixtures and comparison with predicted correlation of reference 1.



(c) Propane, oxygen, helium.

Figure 5. - Concluded. Effect of Reynolds number on turbulent burning velocity for various mixtures and comparison with predicted correlation of reference 1.

3786

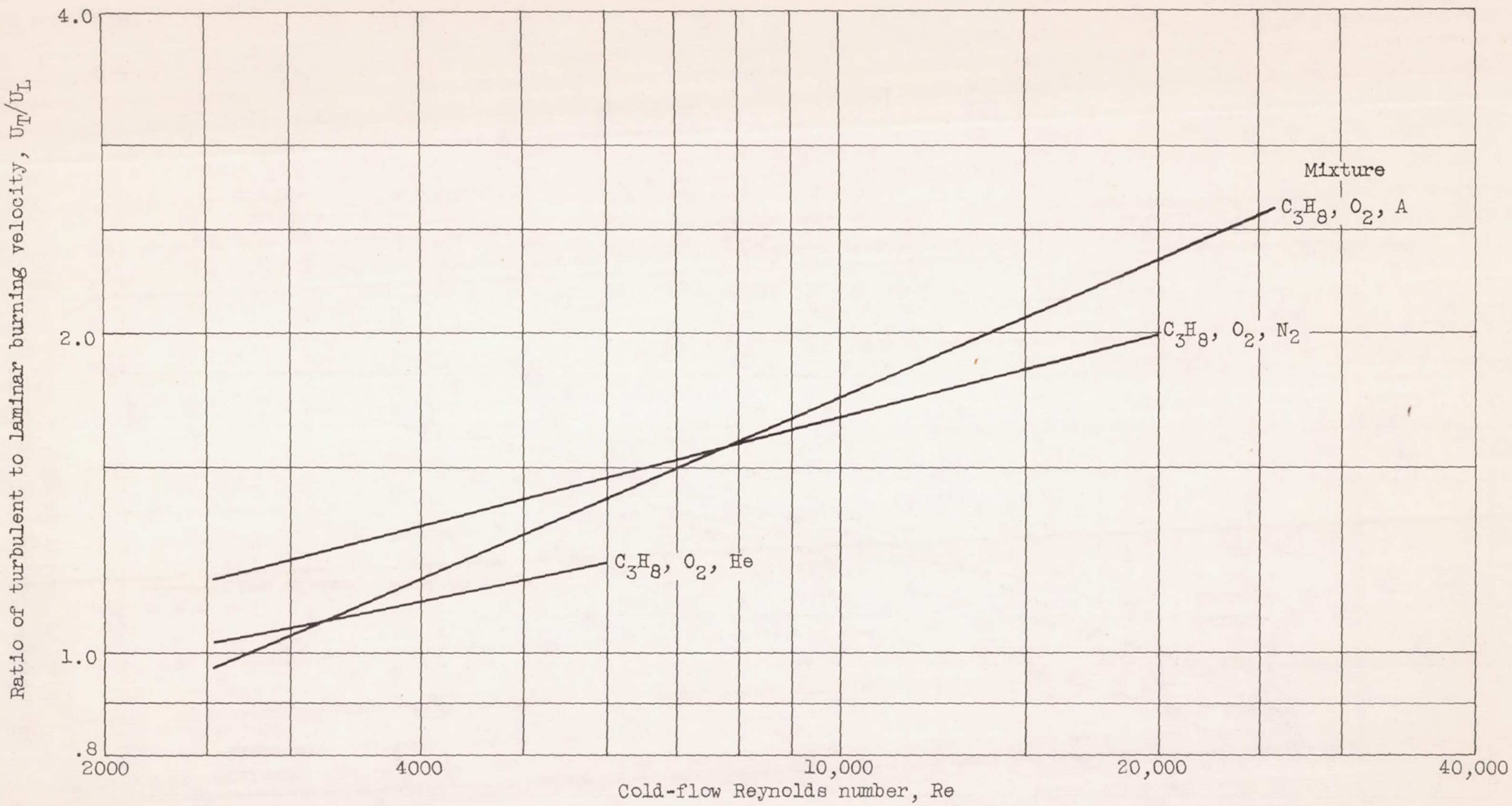


Figure 6. - Summary from figure 5 of turbulent burning velocity dependence on Reynolds number.

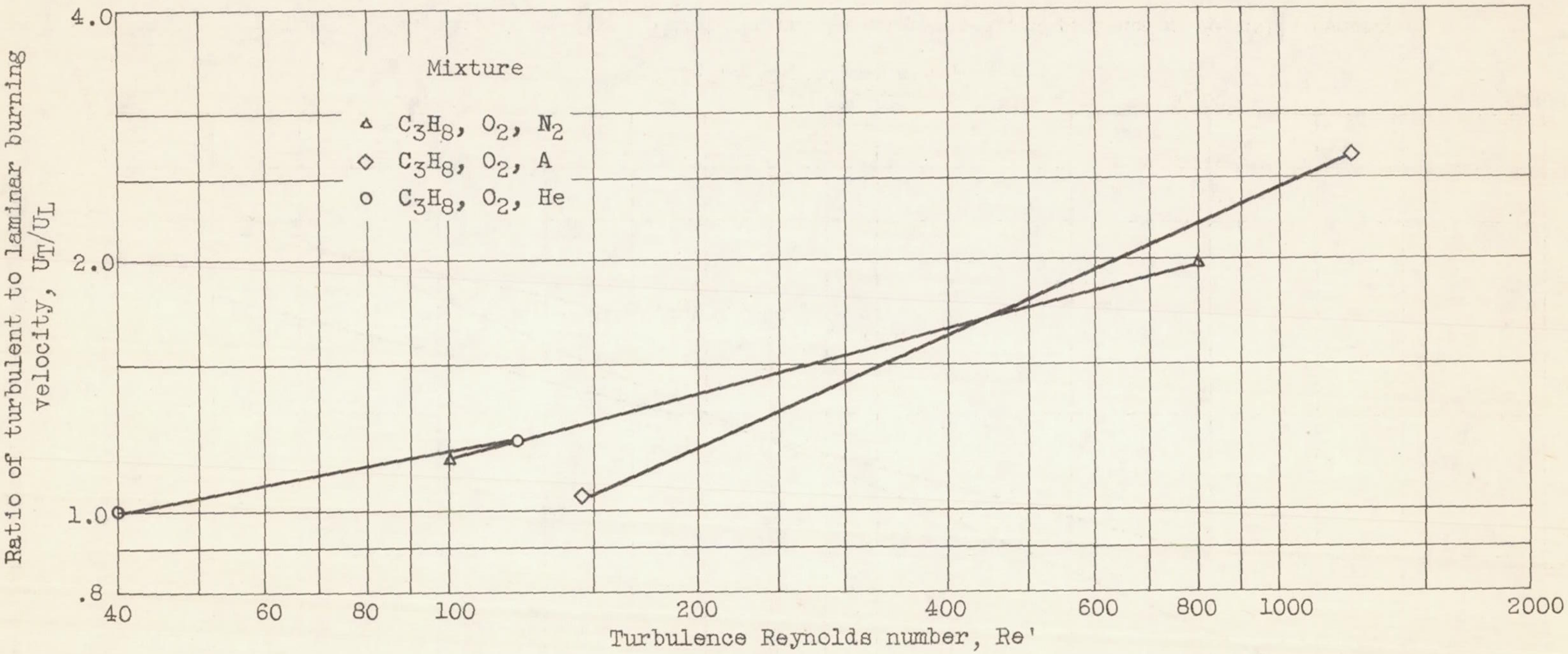


Figure 7. - Turbulent burning velocity as a function of turbulence Reynolds number.

NACA - Langley Field, Va.